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Laboratory-based pressure-broadening data has long provided information that is both of practical importance for technological applications and of fundamental interest for understanding molecular interactions and dynamics. During this project period the temperature dependence of the collision-broadened line widths of H_2O and HDO were studied between 100 k and 600 K. Selected transitions were between 250 GHz and 500 GHz and the broadening gases were O_2, N_2, H_2, and He. Low temperature measurements were made in a collisionally cooled cell to circumvent the limitations imposed by the low vapor pressure of the sample gas at temperatures far below their freezing points. The experimentally determined values were compared with earlier experimental and theoretical works.

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Abstract

Laboratory-based pressure-broadening data has long provided information that is both of practical importance for technological applications and of fundamental interest for understanding molecular interactions and dynamics. During this project period the temperature dependence of the collision-broadened line widths of H_2O and HDO were studied between 100 k and 600 K. Selected transitions were between 250 GHz and 500 GHz and the broadening gases were O_2, N_2, H_2, and He. Low temperature measurements were made in a collisionally cooled cell to circumvent the limitations imposed by the low vapor pressure of the sample gas at temperatures far below their freezing points. The experimentally determined values were compared with earlier experimental and theoretical works.

AFOSR-TR- 94 0184

Final Report

During this project period, the pressure broadening of some selected rotational lines in the ground vibratrional state of H_2O and HDO has been studied in the temperature range between 80 K and 600 K. The broadening gases are He, H_2, O_2, and N_2. This study of condensable gases, H_2O and HDO in particular extends for the first time into the temperature of that low values.

Water is an important constituent of the Earth's atmosphere. Since it plays an important role in atmospheric processes, accurate knowledge of pressure broadening coefficients of water lines is needed to obtain a global picture of its distribution. HDO is a prolate asymmetric rotor with both "a" and "b" transitions. Because of small moments of inertia and large rotational constants, microwave spectra are very sparse. The presence of HDO has been detected in the upper atmosphere as well as in the intersteller medium.

The block diagram illustrating the broadband millimeter and submillimeter (mm/smm) spectrometer used for this investigation is shown in Fig. 1. Briefly, the primary source of the radiation is a 10-15-GHz YIG oscillator. Its output is tripled and drives a 1-W 26-40-Ghz traveling wave tube (TWT) amplifier, whose output is matched onto a harmonic multiplier for the generation of the required mm/smm power (1). The output of the harmonic multiplier is collimated by an electroformed copper horn and propagates quasiopticallly via a series of lenses through the sample cell. Upon exiting the sample cell, the mm/smm waves are propagated into an InSb detector operating at 1.7 K. Data are recorded in the "true lineshape" mode in which the frequency of the system is swept by the microprocessor-controlled synthesizer at a rate, relative th the bandwidth of the system, that the line shape is preserved.

For sample temperatures above 250 K, the measurements are performed in a quartz cell, 10 cm in diameter and 1 m long. For pressure broadening measurements at temperatures far below those imposed by the usual vapor pressure limitations, we use collisional cooling cell (2). The cell temperature can be varied between 80 and 300 K. The upper temperature limit for data collection is set by the freezing point of the sample gas. At each temperature, linewidth measurements are made at about 25 different pressures between 0.05 and 1.0 Torr. Because at the lower pressures the

Doppler width is not negligible compared width the collisional linewidth, a fit to a Voight profile is used to extract the line width $\Delta\nu$. The pressure-broadening coefficient γ for each temperature is obtained from a least-squares fit of the data to the relation

$$\Delta\nu=\gamma P + \Delta\nu_0 \qquad (1)$$

The temperature dependence of pressure-broadening coefficients and pressure-broadening cross-sections are often described by

$$\gamma(T) = \gamma_0(T_0/T)^n \qquad (2)$$

and

$$\sigma(t) = \sigma_0(T_0/T)^m, \qquad (3)$$

where σ_0 and γ_0 are the collisional cross-section and broadening parameter at the reference temperature T_0, respectively, and n and m are constants. The results are usually represented by the above equations (2) and (3). For the temperatures of interest in this work, semiclassical Anderson, Tsao, and Curnutte (ATC)-like theories have ordinarily been used. In these, the interactions are described in terms of multiple expansions of the intermolecular potentials. As might be expected, those interactions described by a single, long-range interaction have produced the best results. Theoretical attempts to determine the temperature dependence of collision-broadened halfwidths are very limited. Even among the few, none of these studies addresses H_2 and He broadening or the issue of low temperature.

Following three publications describe in detail the job performed during the period of this project.

Publication 1: "Variable Temperature Pressure Broadening of the 4(1,4)-3(2,1) Transition of H_2O by O_2 and N_2". The pressure-broadening parameters of the 4(1,4) - 3(2,1) rotational transition in the ground vibrational state of H_2O have been measured in the temperature range between 100 and 520 K. The data were fitted to an exponential temperature-dependence for data above 150 K with resultant n values of

0.81(3) for O_2 and 0.70(3) for N_2. Below 150 K the measured pressure-broadening parameters are smaller than those calculated using these values.

Publication 2: "The Hydrogen and Helium Pressure Broadening at Planetary Temperatures of the 183 and 380 GHz Transitions of Water Vapor." The pressure broadening of the 3(1,3) - 2(2,0) and 4(1,4) - 3(2,1) transitions of water at 183 and 380 GHz, respectively, has been obtained experimentally in the temperature region between 80 and 600 K using H_2 and He as broadening gases. For the lines broadened by He, data were found to fit to the usual power law for the entire temperature range studied with resultant temperature exponent n values of 0.49±0.02 and 0.54±0.03, respectively. For the H-broadened lines the data above 150 K were found to fit to the power law with n values of 0.95±0.07 and 0.85±0.05, respectively. Below 150 K the H_2 pressure broadening parqameters were measured to have smaller values than predicted by the relation.

Publication 3: "The pressure broadening of HDO by O_2, N_2, H_2, and He between 100 K and 600 K." The pressure broadening of the 2(1,1)-2(1,2), 3(1,2)-2(2,1), and 7(3,4) - 6(4,3) transitions of HDO broadened by He, H_2, O_2, and N_2 were studied *in* the temperature region between 80 and 600 K. All He data points for three transitions fit to the power law with n value of 0.5. However, for oxygen, nitrogen, and hydrogen only the higher temperature points can be fit since the data at the lowest temperatures begin to fall below the value predicted by the higher temperature data set.

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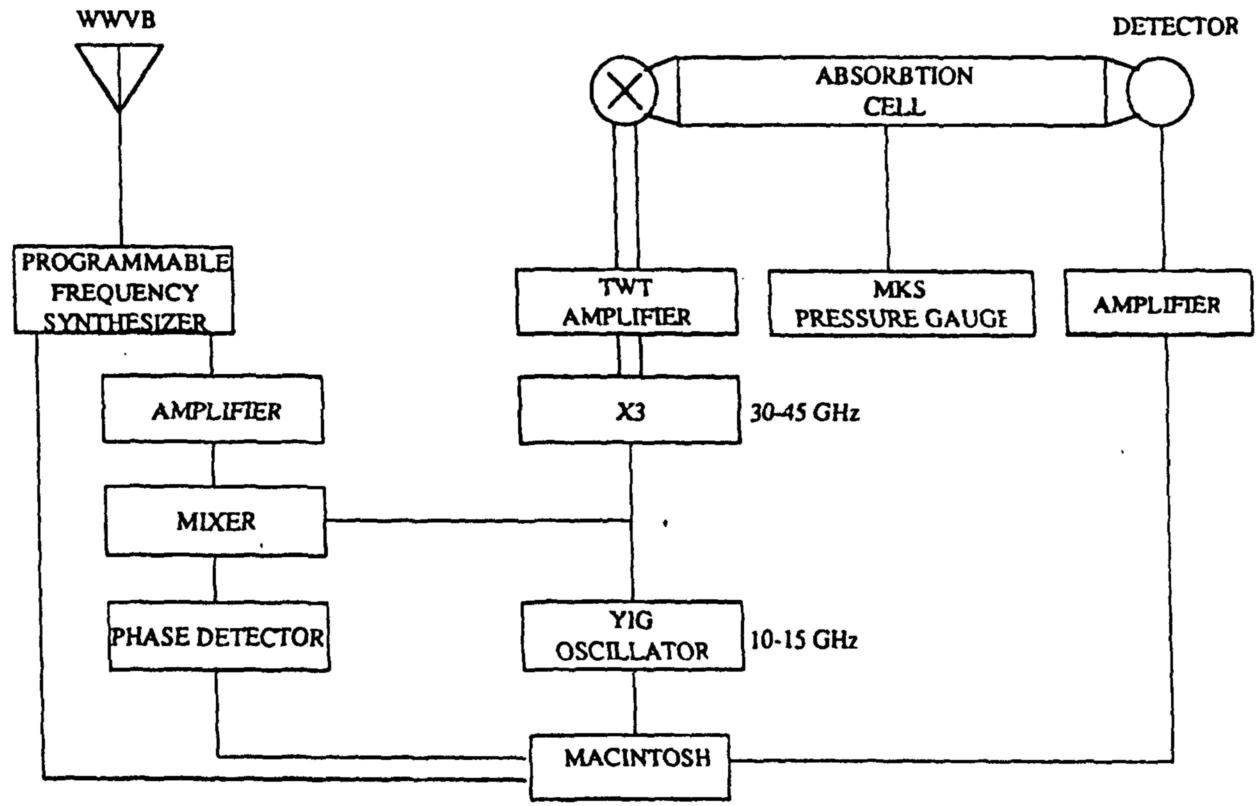

Figure 1. Schematic diagram of the broadband spectrometer.

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The Pressure Broadening of HDO by O_2, N_2, H_2, and He between 100 and 600 K

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Microwave transitions of HDO pressure-broadened by H_2, O_2, N_2, and He were studied in the temperature region between 100 and 600 K. Measurements below 250 K were made in a collisionally cooled cell. Above this temperature a conventional equilibrium cell was used in the region where the HDO has nonnegligible vapor pressure. Significant variations in both the pressure-broadening parameter and its temperature variation were observed among the studied transitions. Below 150 K deviations from the power law ordinarily used to describe the temperature variations were observed. © 1993 Academic Press, Inc.

I. INTRODUCTION

The purpose of this paper is to provide experimental measurements of pressure broadening over a wide range of temperatures. This provides tests for theoretical methods designed to calculate these parameters from a more fundamental set of molecular constants such as dipole and quadrupole moments (*1, 2*). The microwave spectrum of HDO has been the subject of previous studies (*3*). HDO and the collision partners H_2, O_2, N_2, and He were chosen as the subject of this work to compliment earlier work on HNO_3, H_2O, and NO_2 (*4–8*) in order to provide the best possible mix of data for this purpose. Applications in both astronomy and atmospheric science also led to this choice of collision partners. The wide range of temperatures studied in this work is particularly important both to provide for a more stringent theoretical test and because of the many applications at nonambient temperatures. Perhaps the most interesting result of this study is the observation of significant deviations at low temperature from the power law ordinarily used to describe the change of the pressure-broadening parameter with temperature.

II. EXPERIMENTAL DETAILS

We have previously discussed the general millimeter-wave and pressure-broadening techniques used in this work and are brief here (*4, 9, 10*). The measurements at temperatures for which water has a vanishingly small vapor pressure were made in the collisionally cooled cell shown in Fig. 1. In practice its temperature is continuously variable from 80 to 300 K, with the usable upper limit set by the trapping point of the spectroscopic gas. The cell is a 4-inch-diameter copper pipe, 1 foot in length, with 2-inch-diameter end sections with Brewster's angle flanges. Indium-sealed 0.005-inch Mylar windows are attached to the flanges. In order to provide a uniform temperature, the cell is surrounded by a copper jacket 5 feet in length with cooling coils attached, and a 7-foot fiberglass jacket. The spectroscopic sample flows into the cell through the injector seen in the middle of the figure, where the injector temperature is kept above

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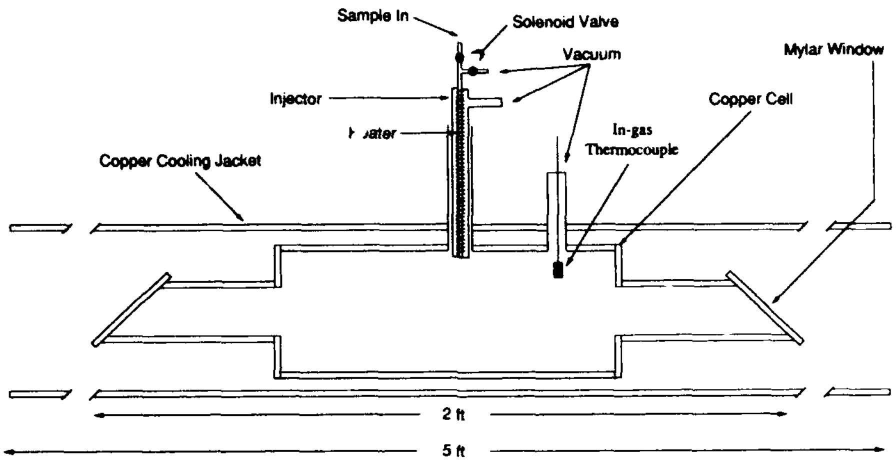

FIG. 1. Collisionally cooled cell for the measurement of pressure broadening at low temperature.

the freezing point of the sample. The cell is filled with a background pressure of broadening gas, and the sample molecules cool by collisions with the cold background gas, eventually random walking their way to the walls where they condense. Higher temperature observations are made in a conventional equilibrium cell which can be cooled by either flowing nitrogen gas or heated electrically. The millimeter radiation is generated by harmonic generation, propagated quasi-optically through the cell, and detected by an InSb detector operating at 1.6 K.

Measurements are made in the collisionally cooled cell by establishing a flow of the spectroscopic gas into the cell from the injector and incrementally adding the collision partner to the cell via a computer-controlled valve. The data acquisition computer then automatically records the lineshape for each of about 40 pressures in the range between ~0.01 and 1.0 Torr. Pressure-broadening parameters are recovered from these data by first fitting them to a Voigt profile to obtain the pressure-broadening

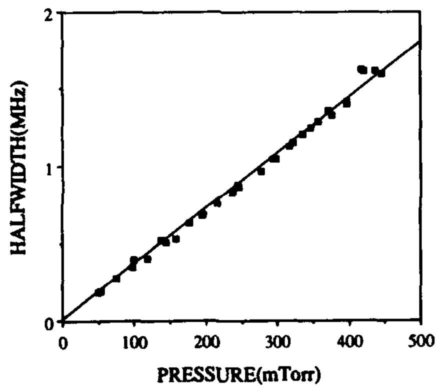

FIG. 2. Measured half-widths as a function of pressure for the $3_{1,2}$–$2_{2,1}$ transition of HDO broadened by H_2.

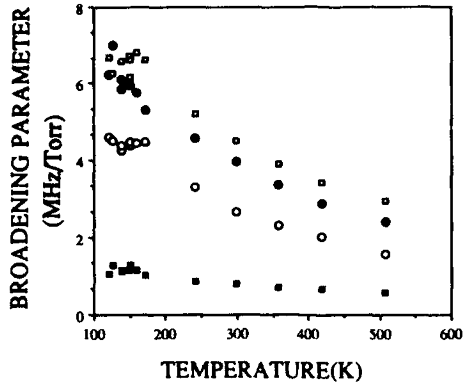

FIG. 3. Pressure-broadening parameter for the $2_{1,1}$–$2_{1,2}$ transition of HDO as a function of temperature for broadening by He (solid square), H_2 (solid circle), O_2 (open circle), and N_2 (open square).

contribution to the lineshape and subsequently fitting these linewidths to the linear function which relates linewidth to pressure and the pressure-broadening parameter. A typical result is shown in Fig. 2. A similar procedure is used in the equilibrium cell, except that initially a small amount (typically 10 mTorr) of HDO is placed in the cell before the broadening gas is incrementally added.

III. RESULTS

Figures 3–5 show the results of the pressure-broadening studies on the $2_{1,1}$–$2_{1,2}$, $3_{1,2}$–$2_{2,1}$, and $7_{3,4}$–$6_{4,3}$ transitions of HDO broadened by He, O_2, N_2 and H_2. These results are also shown numerically in Table I. The variation of pressure-broadening parameter with temperature is often described by

$$\gamma(T) = \gamma_0(T_0/T)^n, \quad (1)$$

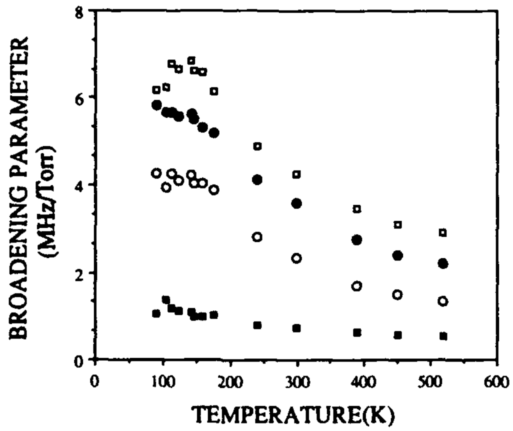

FIG. 4. Pressure-broadening parameter for the $3_{1,2}$–$2_{2,1}$ transition of HDO as a function of temperature for broadening by He (solid square), H_2 (solid circle), O_2 (open circle), and N_2 (open square).

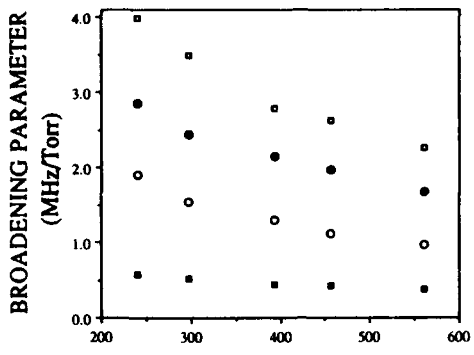

FIG. 5. Pressure-broadening parameter for the $7_{3,4}$–$6_{4,3}$ transition of HDO as a function of temperature for broadening by He (solid square), H_2 (solid circle), O_2 (open circle), and N_2 (open square).

where γ_0 is the broadening parameter at reference temperature T_0 (300 K for this work) and n is a constant. Since this relation has been found to be generally valid near ambient temperatures where most pressure-broadening measurements have been made, it has been used to great advantage to simplify the parametrization of data bases (*11*).

In order to compare the results of our work with this relation, the data of Figs. 3–5 have been replotted logarithmically in Figs. 6–8 and compared with the straight line given by Eq. (1) in the logarithmic representation. In these figures the graphs of Eq. (1) for each case were determined by fitting the higher temperature points for which this relation is valid. The numerical results are shown in Table II. It can be seen in the figures that all helium data points for the three transitions can be fit by this equation. Furthermore, n is found to equal 0.5, the result expected from the simplest hard sphere theory. However, for oxygen, nitrogen, and hydrogen only the higher temperature points can be fit since the data at the lowest temperatures begin to fall below the value predicted by the higher temperature data set.

IV. DISCUSSION

The number of observations of pressure broadening for polyatomic molecules over a relatively large range of temperature is small. Observations have now been made over the region from ~100 to 600 K for HNO_3, H_2O, and HDO in collision with H_2, He, O_2, and N_2 (*5–7*). The broader temperature range covered by this work leads to both more accurate values of n and observations of deviations from Eq. (1). Thus, they provide a particularly interesting set of experimental results against which theories can be developed and tested.

For this work on HDO there is a large variation of room temperature pressure-broadening parameter γ_0 with quantum number, which can be easily seen both in the graphs and in Table II. For all broadening gases the pressure-broadening parameter decreases with increasing J and energy, the largest change occurring in oxygen broadening where there is a decrease of 42%. The n values for helium show no significant change with quantum number from the classically predicted $n = 0.5$, a result that indicates the collision cross sections are remaining constant. However, there is significant variation in the value of n for collisions involving oxygen, nitrogen, and hydrogen.

TABLE I

The He, H_2, O_2, and N_2 Broadening Parameters of HDO[a]

T(K)	γ(MHz/Torr) He	H_2	O_2	N_2
		$2_{1,1}$-$2_{1,2}$ 241561.55 MHz		
121	1.06	6.25	4.60	6.70
127	1.28	7.01	4.51	6.27
139	1.15	6.12	4.37	6.59
139	1.11	5.84	4.27	6.58
149	1.14	6.02		6.71
150	1.27		4.37	6.18
151	1.18	5.96	4.49	6.61
160	1.16	5.75	4.44	6.80
171	1.04	5.31	4.49	6.63
241	0.86	4.58	3.29	5.21
298	0.80	3.97	2.67	4.51
357	0.71	3.35	2.31	3.89
419	0.66	2.87	2.01	3.41
508	0.59	2.39	1.58	2.95
		$3_{1,2}$-$2_{2,1}$ 225896.70 MHz		
90	1.07	5.81	4.25	6.19
105	1.37	5.68	3.94	6.24
113	1.17	5.68	4.25	6.77
124	1.12	5.58	4.10	6.67
142	1.09	5.62	4.22	6.85
147	1.00	5.51	4.03	6.61
159	0.99	5.32	4.04	6.61
175	1.03	5.20	3.88	6.14
241	0.79	4.12	2.81	4.88
298	0.74	3.59	2.33	4.26
388	0.63	2.74	1.71	3.45
450	0.59	2.40	1.50	3.10
518	0.55	2.20	1.35	2.90
		$7_{3,4}$-$6_{4,3}$ 241973.50 MHz		
241	0.57	2.86	1.90	3.99
298	0.52	2.44	1.54	3.49
394	0.45	2.15	1.29	2.79
457	0.42	1.97	1.11	2.63
561	0.37	1.68	0.96	2.27

a. Absolute uncertainty estimated at ±10%. Relative uncertainty estimated at ±5%.

The largest change occurs in the hydrogen broadening, for which the value of n changes by 31%. This result is easily seen in the plot of hydrogen broadening where the data set for $7_{3,4}$–$6_{4,3}$ has a significantly different slope from the other transitions.

Perhaps the most interesting results in this work are those obtained at temperatures below ~150 K, where deviations from Eq. (1) occur for all collision partners except He. All semiclassical Anderson-like theories predict that there exists a temperature below which the Fourier components of the collision are no longer effective for the creation of broadening. These are manifest in the parameter $k = (b/\omega)/v$ which effectively compares the Fourier frequencies produced by the molecule passing with velocity v within collision parameter b and the rotational transition frequency ω (*12*). In this context it is no surprise that helium is the most hard sphere-like. It has no internal degrees of freedom to come into resonance with the Fourier components of

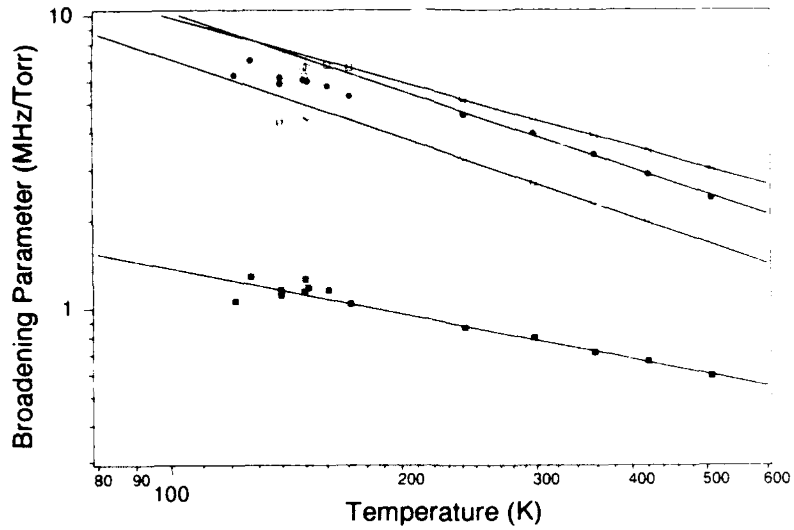

FIG. 6. Log plot of the pressure-broadening parameter for the $2_{1,1}$–$2_{1,2}$ transition of HDO as a function of temperature for broadening by He (solid square), H_2 (solid circle), O_2 (open circle), and N_2 (open square).

the collision and the energy levels of HDO connected to the observed transitions are, although relatively widely spaced, closely spaced in comparison to the spectrum of the collision. Although H_2 is even lighter than He and thus in collisions produces even

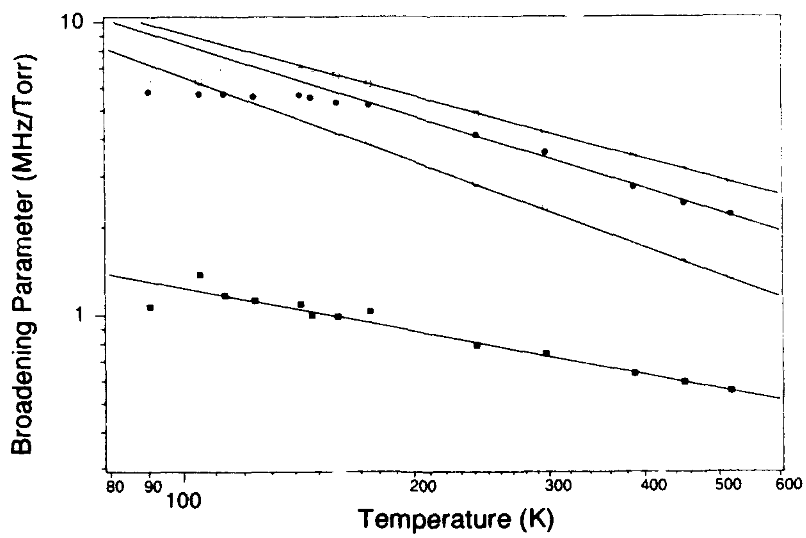

FIG. 7. Log plot of the pressure-broadening parameter for the $3_{1,2}$–$2_{2,1}$ transition of HDO as a function of temperature for broadening by He (solid square), H_2 (solid circle), O_2 (open circle), and N_2 (open square).

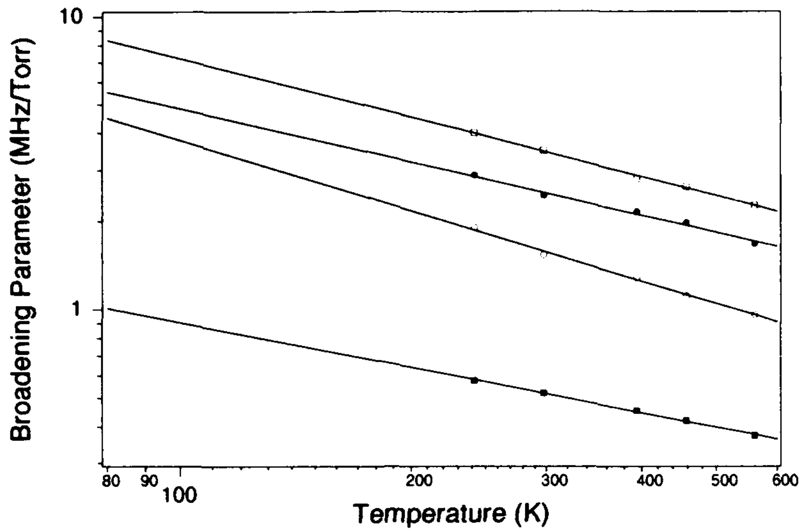

FIG. 8. Log plot of the pressure-broadening parameter for the $7_{3,4}$–$6_{4,3}$ transition of HDO as a function of temperature for broadening by He (solid square), H_2 (solid circle), O_2 (open circle), and N_2 (open square).

a broader spectrum, it has very widely spaced rotational energy levels of its own which can participate in the energetics of the collision. In fact, we find in our previous studies the decrease in observed cross section below that given by Eq. (1) to be a general feature of H_2 broadening. For example, Figs. 9 and 10 show the H_2 pressure-broadening parameters of the $3_{1,3}$–$2_{2,0}$ and $4_{1,4}$–$3_{2,1}$ transitions of H_2O, respectively. Comparison with the He results leads to a strong indication that this effect is due to the internal energy levels of H_2 (*7, 8*). The O_2 and N_2 results show a similar short fall. Again this result is consistent with our observations on other species (*4, 6*). However, in these cases both O_2 and N_2 are much heavier than either H_2 or He and the appropriate

TABLE II

HDO Pressure Broadening Parameters[a,b]

		$2_{1,1}$-$2_{1,2}$	$3_{1,2}$-$2_{2,1}$	$7_{3,4}$-$6_{4,3}$
Helium	n	0.50(5)	0.52(3)	0.50(5)
	γ_0	0.78(1)	0.74(1)	0.52(1)
Hydrogen	n	0.86(5)	0.81(2)	0.59(3)
	γ_0	3.9(1)	3.48(3)	2.51(4)
Oxygen	n	0.90(3)	0.96(2)	0.81(6)
	γ_0	2.71(5)	2.25(2)	1.58(5)
Nitrogen	n	0.77(1)	0.70(2)	0.67(5)
	γ_0	4.45(6)	4.21(4)	3.47(6)

a. γ in MHz/Torr.
b. Uncertainties are 1 standard deviation taken from fit.

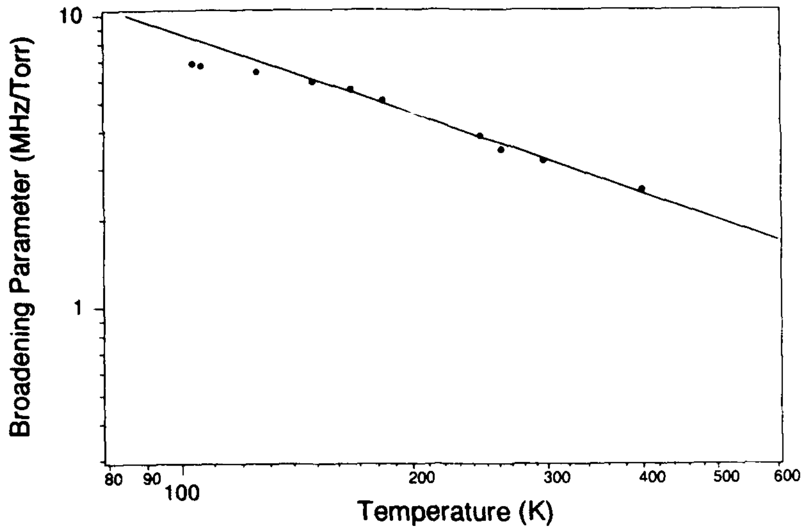

FIG. 9. The H_2 pressure-broadening parameters of the $3_{1,3}$–$2_{2,0}$ transition of H_2O.

comparison should be between the much lower frequency spectrum produced in their collisions and the energy level spacings of HDO and O_2 and N_2 themselves.

Finally, it should be noted that in other work which has extended these measurements to very low temperatures (~4 K) significant new phenomena associated with quasi-bound states are observed for collisions with both H_2 and He (*13*). Specifically, these quasi-bound states lead to the formation of large resonances in the pressure-broadening

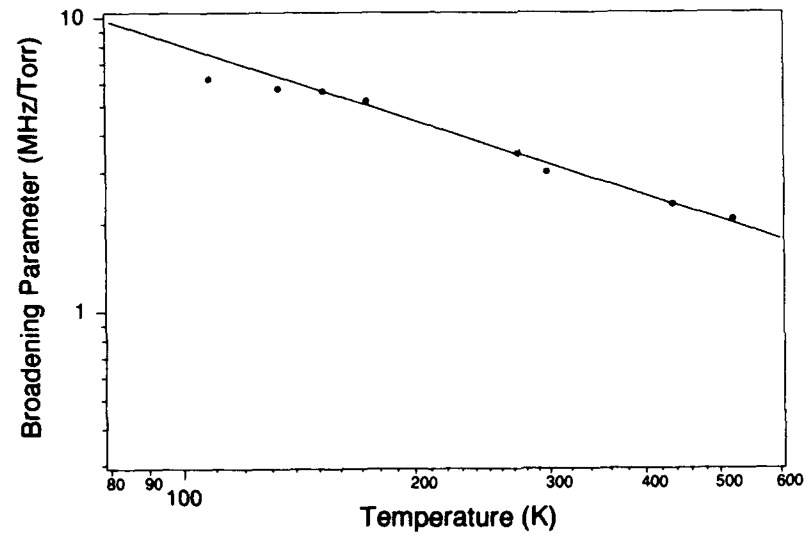

FIG. 10. The H_2 pressure-broadening parameters of the $4_{1,4}$–$3_{2,1}$ transition of H_2O.

cross sections at low temperature. Thus, although the semiclassical theory considered here leads unambiguously to a lowering of cross section at very low temperature, these new processes often lead to significantly increased cross sections at low temperature.

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COMPLETED PROJECT SUMMARY

TITLE: High Resolution Molecular Spectroscopy of Atmospheric Species

PRINCIPAL INVESTIGATOR:	Jyotsna M., Dutta Charles R. Jones Department of Physics North Carolina Central Univ. Durham, NC 27707
INCLUSIVE DATES:	01 July 1989 - 30 Sept 1993
CONTRACT/GANT NUMBER	F49620-89-C-0080
COST AND FY SOURCE:	$250,740
SENIOR RESEARCH PERSONNEL:	J. M. Dutta C. R. Jones W. Ebenstein
JUNIOR RESEARCH PERSONNEL:	Ralph France Thomas L. Edwards

Publications

1. J. M. Dutta, C. R. Jones, T. M. Goyette, and F. C. DeLucia, "The Hydrogen and Helium Pressure Broadening at Planetary Temperatures of the 183 and 380 GHz Transitions of Water," ICARUS, Vol. 102, 232-239(1993).

2. T. M. Goyette, F. C. Delucia, J. M. Dutta, and C. R. Jones, "Variable Temperature Pressure Broadening of the 4(1,4)-3(2,1) Transition of H_2O by O_2 and N_2," J. Quant. Spectrosc. Radiat. Transfer Vol. 49, 485-489(1993).

3. J. M. Dutta, T. M. Goyette, D. W. Ferguson, F. C. DeLucia, and C. R. Jones, "The Pressure Broadening of HDO by O_2, N_2, H_2, and He between 100K and 600K," J. Mol. Spectrosc 162, 366-374 (1993).

Presentation of papers in national and international meetings (recent ones)

(with) T.M. Goyette, F. C. Delucia, and C. R. Jones, "Pressure Broadening Of SO_2 Between 90K and 600K", Conf. Digest 18th Int. Conf. on IR & MM Waves, Univ. of Essex, UK, pp. 82-83(1993).

(with) C. R. Jones, T. M. Goyette, and F. C. DeLucia, "Variable Temperature Pressure Broadening of SO2", Symposium on Molecular Spectroscopy, Ohio State Univ., Columbus, OH June 14-18, '93.

(with) C.R. Jones, T.M. Goyette, D.W. Ferguson, and F.C. DeLucia,"Pressure Broadening of H_2O and HDO Between 90 K and 600 K", Conf.Digest 17th International Conf. on IR & MM Waves, Calif. Inst. of Tech., p.176(1992).

(with) T. M. Goyette, D.W. Ferguson, C.R. Jones, and F.C. DeLucia,"Pressure Broadening of HDO Between 90 K and 600 K", 47th Int. Symp. on Mol. Spectros., Columbus, OH (1992).

(with) T. M. Goyette, C.R. Jones, and F. C. DeLucia, "Microwave Spectroscopy at 80K", Bull. Am. Phys. Soc., **37**, 520(1992).

(with) T. M. Goyette, C. R. Jones, and F. C. DeLucia, "Temperature Dependences of Pressure-Broadened HDO Lines in the Millimeter Wave Region", Bull. Am. Phys. Soc., V. 30. p.2731(1991)

ABSTRACT OF OBJECTIVES AND ACCOMPLISHMENTS:

This project was involved in far infrared measurement on temperature dependence of pressure broadening of selected lines of molecular species of atmospheric importance. Topics studied are listed below:

(1) The pressure broadening of the 3(1,3)-2(2,0) and 4(1,4)-3(2,1) transitions of water at 183 and 380 GHz, respectively, has been studied in the temperature region between 80 and 600 K. The broadening gases used were O_2, N_2, H_2, He.

(2) The pressure broadening studies on the 2(1,1)-2(1,2), 3(1,2)-2(2,1), and 7(3,4)-6(4,3) transitions of HDO at 242, 226, and 242 GHz, respectively, broadened by He, O_2, N_2, and H_2 in the temperature region between 80 and 600 K has been conducted.

(3) Dependences of room temperature pressure broadening parameters and the temperature exponents with the rotational quantum numbers were investigated.

(4) This extends for the first time the study of condensable gases in general and H_2O and HDO in particular to such a wide range of temperature.

AFOSR Program Manager: James G. Stobie Lt. Col.
Dr. James Kroll